Integrated Solar and Radio-Frequency Energy Harvesting for the Internet of Everything

Tammy Chang, Jonathan A. Fan, Thomas H. Lee

***Abstract*—To reach the level of ubiquitous deployment expected for the Internet of Everything (IoE), energy harvesting is a promising and necessary functionality for providing power to a high volume of wireless devices, and will require harvesting from multiple sources to increase the lifetime and reliability of IoE devices. The research objective of this project was to develop a compact module to harvest both solar energy as well as radio-frequency (RF) energy with a single physical aperture, enabling dedicated RF and ambient solar energy harvesting within a compact form factor. This was accomplished with a three-dimensional printed antenna design that enables high optical transmission without compromising the radiation efficiency of the RF antenna, such that it may be mounted above a solar panel and provide stable power delivery for IoE functionality. The results of this project are summarized in this report.**

***Index Terms*—Solar, radio frequency, energy harvesting, Internet of Things, three-dimensional printing**

I. Introduction

CURRENTLY, a rapid increase is expected in the number of deployed wireless devices, rising to 50 billion connected devices by 2020 [1]. To enable this level of ubiquitous deployment, these devices must be able to have long-term and self-sustaining power sources, due to the volume of devices deployed. For this reason, energy harvesting from remote sources is attractive as a potential solution, and the integration of multiple energy harvesters has been proposed for robustness to changes in the surrounding environment [2]. Among the potential energy sources considered, radio-frequency (RF) power has been proposed by researchers as a dedicated source while solar power has been proposed as an ambient source, so that a primary and auxiliary source of energy can both be harvested.

In this project, we propose the integration of these two energy-harvesting methods within a single, compact IoT module. The combination of both energy-harvesting mechanisms would allow a more robust system that can achieve higher power delivery for IoT operations, as well as a significantly reduced form factor. Our proposed system provides a solution where the antenna does not obstruct the light that the solar cell would otherwise collect, by utilizing a three-dimensional printed antenna design that enables high optical transmission without comprising the radiation efficiency of the RF antenna.

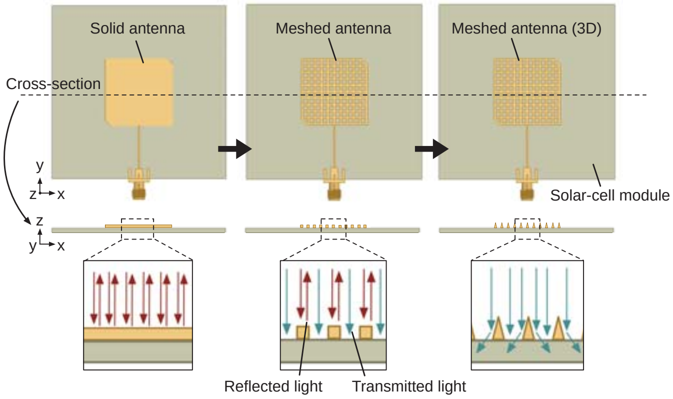

Fig. 1. Transition to a highly optically transmissive antenna utilizing a three-dimensional geometry.

II. 3D Antenna Design for High Efficiency Energy Harvesting

As expected, mounting a RF antenna, typically designed with non-transparent metal, above a solar cell would inevitably result in lowering the efficiency of the solar cell, due to the physical obstruction of light. Recent methods have used meshing techniques to cut holes in the geometric plane of the antenna to increase its optical transparency [4]. This approach results in RF losses in the metal, degrading the radiation efficiency of the antenna, and still obstructs light in areas where the mesh lies. We have developed a design for the antenna that would increase the energy harvesting efficiency for both solar and RF sources [5]. This is done with a three-dimensional structure, as shown in Fig. 1.

In concept, light no longer backscatters when it hits the metal surface of the antenna. Instead, the three-dimensional structure of the antenna reflects light through the antenna so that it can still be harvested by a solar cell placed behind it. Meanwhile, the triangular structure allows larger surfaces of high conductivity metal for RF surface current to travel along, minimizing the RF loss that results from extremely narrow lines in the planar meshed antenna.

III. Fabrication and Measurements

This antenna design is feasible due to recent progress in three-dimensional manufacturing. We have developed a fabrication process that allows us to create a 3D model and selectively metallize specific surfaces to create the proposed structure [5]. High-resolution prototypes were fabricated with an extrusion-based Solidscape 3D Wax Printer, as shown in Fig. 2. The wax molds were re-cast in silicone molds (Mold

The authors are all with the Department of Electrical Engineering, Stanford University, Stanford, CA, 94305 USA (e-mails: tammyc@stanford.edu, jonfan@stanford.edu, tomlee@ee.stanford.edu). T. Chang is co-advised by J. A. Fan and T. H. Lee, who are the Principal Investigators of the Stanford Applied Nanophotonics Laboratory and Stanford Microwave Integrated Circuits Laboratory, respectively.

Max 30, Smooth-On) and then cast with ultraviolet-resistant clear epoxy (EpoxAcast 690, Smooth-On). The antenna was metallized with silver print (Silver Print, MG Chemicals). For high-quality metallization of silver and copper, sophisticated microfabrication techniques can be implemented.

The return loss of the dipole antenna was measured using an Agilent E8361A PNA Network Analyzer, and compared with simulation. The measurement and simulation results share similar resonance peaks between 1 and 5 GHz. Differences in the magnitude of the return loss are attributed to conductive loss from the silver print metallization. Additionally, the measured dipole resonance is shifted downward from 2.4 GHz to 2.3 GHz. This is likely due to dielectric loading from cured epoxy which is used to secure the SMA feed to the antenna.

Because the objective of this project involved co-designing the antenna with the solar cell module, the impact on solar efficiency was evaluated with an off-the-shelf solar cell module (Sunnytech Mini Solar Panel, 0.5 W, 80 × 80 mm) for initial characterization, as shown in Fig. 4. When the solar cell is exposed to indoor lighting, the open-circuit voltage measured by a digital multimeter is 3.075 V. Next, a meshed 3D sample was placed above the solar cell, and the open-circuit voltage of the solar cell dropped to 3.041 V. In comparison, a solid 2D sample and meshed 2D sample would yield an open-circuit voltage of 2.950 V and 2.981 V, respectively. From Table I, it is evident that the initial prototype provides increased transmission efficiency. For a larger antenna that consumes a greater proportion of area above the solar cell, the gain in transmission would be even greater.

IV. CONCLUSION

In this project, the integration of solar and radio-frequency energy harvesting within a compact module was investigated. The same aperture is used for two energy harvesting domains by mounting a highly optically transmissive antenna above a solar-cell module. 3D printing and microfabrication techniques are utilized to achieve the desired antenna design, and the return loss is measured. The optical transmission efficiency of the antenna is measured using an off-the-shelf solar cell module, and results indicate that the proposed three-dimensional antenna provides high optical transmission efficiency. Next steps involve developing the energy harvesting circuit component to harvest solar energy and RF energy as ambient and dedicated sources, respectively.

FUTURE PLANS OF THE RECIPIENT

I am presently preparing my dissertation for graduation this year. Afterwards, I hope to work in industry, with the possibility of returning to academia in the future. Being a part of the MTT-S Fellowship program has given me the opportunity to pursue a research project that involved new experimental approaches, and established my confidence that I can similarly pursue original research ideas in my future career. Furthermore, the opportunity to attend IMS 2017 allowed me to engage with and present my work to experts in my areas of interest. I am incredibly grateful for the MTT-S Fellowship program and the benefits it has provided to me in my professional development.

Fig. 2. Images of the fabrication process of prototyped 3D antennas and transmission lines with varied meshing patterns.

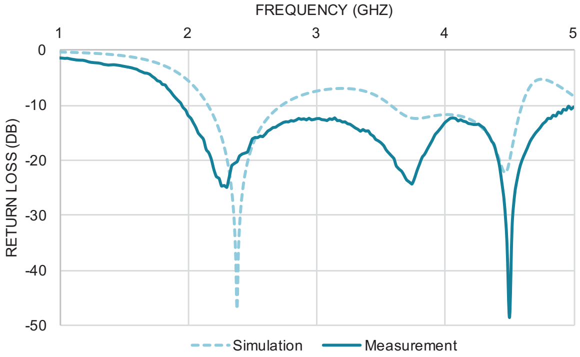

Fig. 3. Images of the fabrication process of prototyped 3D antennas and transmission lines.

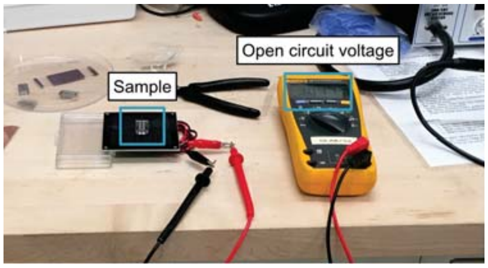

Fig. 4. Images of the fabrication process of prototyped 3D antenas and transmission lines.

TABLE I
COMPARISON OF SOLAR CELL TRANSMISSION EFFICIENCY FOR DIFFERENT ANTENNA DESIGNS

Sample Type	V_{oc} (V)	Transmission Efficiency (%)
Solid	2.950	95.9
Meshed	2.959	96.2
Meshed (3D)	3.041	98.9
None	3.075	100.0

REFERENCES

[1] D. Evans, "The Internet of Things: How the Next Evolution of the Internet is Changing Everything," Cisco White Paper, 2011.
[2] P. Kamalinejad, C. Mahapatra, Z. Sheng, S. Mirabbasi, V. C. M. Leung, Y. L. Guan, "Wireless Energy Harvesting for the Internet of Things," *IEEE Commun. Mag.*, vol. 53, no. 6, Jun. 2015.
[3] T. Shahvirdi, R. Baktur, "A Study on the Effect of Space Solar Cells on the Antennas Integrated on Top of their Cover Glass," *Proc. IEEE Antenn. Propag. Soc. Int. Symp.*, Memphis, TN, USA, Jul. 2014.
[4] J. Hautcoeur, L. Talbi, K. Hettak, "Feasibility Study of Optically Transparent CPW-Fed Monopole Antenna at 60 GHz ISM Bands," *IEEE Trans. Antenn. Propag.*, vol. 61, no. 4, pp. 1651–1657, Apr. 2013.
[5] T. Chang, J. Fan, "Three-dimensional Device with Multi-functional Electromagnetic Properties," U.S. Provisional 62/337,231, May 2016.